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Shape predominant effect in pattern recognition of geometric figures of rhesus monkey

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Abstract

Three monkeys were trained successively with discrimination, concurrent matching to sample, and sameness–difference judgment tasks in which learning curves were compared. Then, the display duration for the stimuli was shortened to 100, 50, and 30 ms respectively to test the changes in accuracy and reaction time. All results in three experimental paradigms suggested consistently that the geometric shape (triangle, circle, and square) plays a more predominant role than topological features (the hole inside of a figure and the hole numbers) in monkey figure recognition. The results are different from the experiment by human subjects who presented hole predominant in figure recognition. Therefore, the precedence in perception depends on subject species, stimulus set, and ecological significance of the perceiving process.

Keywords: Rhesus monkey; Pattern recognition; Topological feature; Euclid geometric property; Species-specific effect

1. Introduction

The studies on pattern recognition of two-dimensional (2D) images was a frontier of artificial intelligence (AI) three decades ago, but the difference of visual perception among machine, human, and non-human primates remains to be revealed. AI pays attention to machine perception, which usually starts from feature detection with analysis of gray level, line finding, region growing, geometric shape differentiation (Cohen & Feigenbaum, 1982). On the contrary, Gestalt psychology claims that human visual perception concerns predominant processing of global features. The theory of global predominance over local features was advanced on the basis of findings which used compound stimulus patterns with small letters nested within a larger letter (Navon, 1977, 1983). The global feature is formally identified with the properties of larger letters, which is composed of smaller ones, and the local feature is defined by the features of the small letters. Furthermore, topological theory was advanced on the basis of the evidences in figure recognition (Chen, 1982, 1984), "these global properties can be described mathematically as topological properties, such as connectivity". A hole in a figure breaks down the figure's connectivity, therefore ring–circle is topologically different, while triangle–circle is topologically equivalent. Three pairs of geometric figures were used in experiment 1 (Chen, 1982) and each exposure of them was controlled by a tachistoscope for 5 ms. Human subjects were asked to judge whether the two figures in each exposure were the same or different. The results showed that the accuracy was 64.5% for ring–circle pairs, 43.5% for square–circle, and 38.5% for triangle–circle pairs respectively. In experiment 2, two pairs of geometric figures were learning (Chen, 1990), and the accuracy was 66.2% for the pairs of circle with one hole or two holes, 39.0% for square–circle pairs respectively. Therefore, human visual system is more sensitive to hole and its number inside a black circle than the geometric shape differences of the stimulus figures (Chen, 1986, 1989).

Does the perception precedence of topological properties also exist in non-human primates? If so, the neural substrate under this perception precedence might be explored with electrophysiological methods. For this purpose, three behavioral paradigms were designed to elucidate this issue. The discrimination task (DT) emphasized the judgment of differences between two figures (Aston-Jones, Rajkowski, & Kubiak, 1997; Anderson, 1998; Kobatake, Wang, & Tanaka, 1998), and the

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concurrent matching to sample (CMS) task focused on the sameness judgment in the figures (Naya, Sakai, & Miyashita, 1996; Gutnikov, Ma, Buckley, & Gaffan, 1997). Go/no-go task was conducted further more to investigate both of the sameness and difference judgments. Three behavioral experiments were consistent with weighted ratio model that covered both the common and different parameters among the objects (Lamberts, 1994).

2. Experiment 1: discrimination task

It's well known that monkey's inferotemporal neurons are sensitive to 2D geometric shape since 1972 (Gross, Rocha-Miranda, & Bendeer, 1972). Also the effects of shape-discrimination training on the neuron selectivity were reported (Kobatake et al., 1998), however, the learning process of discriminating geometric figure (Sáry, Vogels, & Orban, 1993; Missal, Vogels, & Orban, 1997) remains unknown. In this experiment, the leaning process of figure discrimination was compared and the presentation duration was shortened step by step to inquire into the critical attribute of figures in early visual processing.

2.1. Materials and methods

Three female adult rhesus monkeys (*Macaca mulatta*) weighing around 5 kg were used for the experiment. They were identified as DAG, DAX, and NIN. The experimental protocol was approved by the Animal Care and Use Committee of Beijing City Government for training and experiments performed with monkeys.

All stimuli were generated by computer and displayed on a CRT screen. The viewing distance was 15–20 cm. The illumination and contrast of the screen were kept stable during all the procedures. A black cross was exposed in the center of the screen as a fixation point for 1 s initially, followed by two figures displayed randomly at both sides of the screen for 1 s. Monkeys were trained to perform a DT and point the positive figure. Stimuli displays disappeared as soon as monkeys touched the screen and food reward (a peanut) was delivered upon correct response. Three series of figure pairs were used in this task (Table 1). P–Ns pairs presented Euclid geometric distinction (different shape). P–Nh displayed obviously the topological distinction (the hole, and the number of holes), but carried high Euclid geometric similarity. P–Nsh bore the differences of both P–Ns and P–Nh. These three groups of figures were designed to detect the role of hole property including hole number in the process of discrimination judgment. Monkeys were trained five days a week on the same schedule for each day. Forty trials were run under each of the two blocks

Table 1
Three groups of figure used in training and perception detection

Group	Positive figure P	Negative figure Ns	Negative figure Nh	Negative figure Nsh
1				
2				
3				

P stands for positive stimulus, N for Negative stimulus, s for shape, h for hole and sh for shape and hole differences.

every training day. After accuracy of the DT was kept above 80% in five successive training days, monkeys were considered being successfully trained. Then a perceptual detection procedure was conducted with the stimuli display time shortened to 100, 50, and 30 ms randomly.

After the DT, the hole size of all figures Nh in group 1 and group 3 were enlarged. The ratio of inner hole diameter to circle diameter was increased to 1:3, 1:2.5, 1:2, and 1:1.5 randomly across blocks. Accuracy and reaction (RT) of the discrimination performance were measured with the display time of 30 ms.

After all the data from the daily collection were pooled for this experiment, the learning processes of different groups of figure in these three monkeys were compared. All data were processed with SPSS package (Version 10.0, SPSS Inc., Chicago, IL, 1999) using analysis of variance (ANOVA).

2.2. Results

It took a long time to train the monkey to discriminate two figures. Fig. 1 shows the training days needed for the monkey to reach accuracy of 85% in different groups. The results demonstrated it took longer period (13–20 days) to learn to discriminate two figures with topological distinct (P–Nh) than two figures with shape distinction (P–Ns) and two figures with both distinct (P–Nsh) which took 5–10 days (Fig. 2). The learning process was similar among these three groups of figures.

The differences of RT did not reach significance level. Accuracy of P–Nh pair changed significantly when the display time was shortened to 30 ms in three groups. Especially, accuracy of P–Nh pair of the second group began to decrease when the display time was shortened to 50 ms (Table 2).

When the ratio of the diameters between the inner hole and outer diameter was enlarged from 1:3 to 1:2 and 1:1.5, the discrimination of figure distinction was well performed by monkeys (Fig. 3).

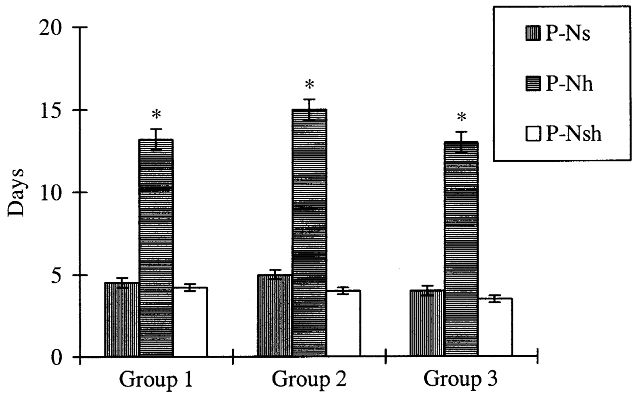

Fig. 1. Comparisons of the learning difficulties in DT. *Y*-axis represents training days spent for accuracy up to 80% in different groups of geometric figure. P–Ns, P–Nh, and P–Nsh are pairs of stimulus figures, P stands for positive stimulus, N for negative stimulus, s for shape, h for hole and sh for shape and hole differences. $^*P < 0.05$, ANOVA among three pairs of figure in different groups respectively ($n = 3$).

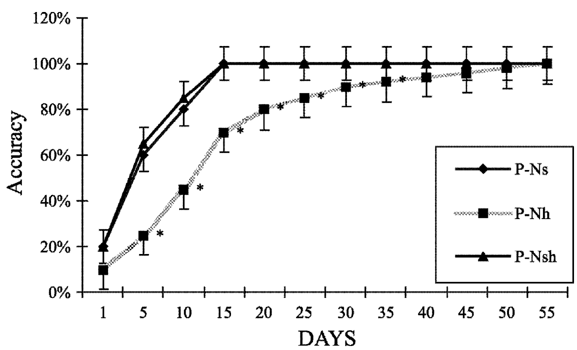

Fig. 2. The learning curves of the monkeys to three groups of stimulus. $^*P < 0.05$, ANOVA among three pairs of figure ($n = 3$). Fractions in the figure represent the ratio of the diameter of the hole and the circle.

2.3. Discussion

Monkey's learning curves demonstrate that it is much easier for monkeys to learn the discrimination of the difference in Euclidean geometric shapes. Their discrimination to shapes remains perfect even when the presentation time was shortened to 30 ms. It's consistent with the finding that the shape selectivity of inferior temporal neurons is independent of the size, position, motion, luminance and texture (Sáry et al., 1993). It should also be noted, however, that the current results

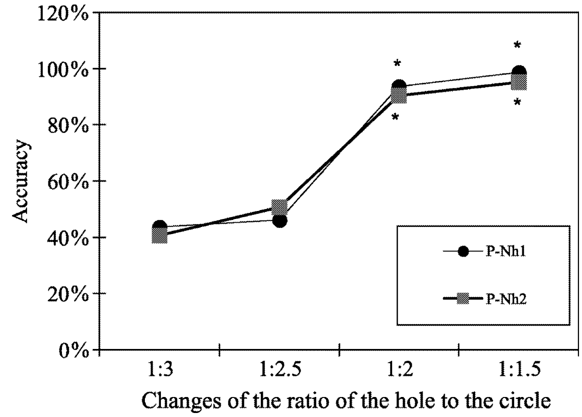

Fig. 3. Effect of hole size to the accuracies of DT. $^*P < 0.05$, ANOVA among A–D ($n = 3$). Nh1, with one hole in the circle, Nh2, with two holes in the circle. The display duration is 30 ms.

are different from those of human subjects who have higher accuracy for ring–circle pairs than the pairs with shape difference (Chen, 1982, 1990). It might be due to the differences in the stimuli, the ratios of the diameters between the holes and the black circles are different from each other. In the experiment with human subjects, the ratio was 1:1.77 (18 mm for the hole diameter, 32 mm for the circle diameter). Considering the result that Ss' performance become better when the hole size increases, one might have thus predicted that the hole size has an great impact on the perception of the geometric figures. Although the topological properties do not change between the small-hole negative figure and large-hole negative figure, the discrimination performance changed significantly. The different result we get from this experiment might be due to the change of the geometric properties of the figures, since a circle with a large hole may be regarded as a ring instead of a circle with a hole. When it happens, the inside hole is no longer perceived as a hole. This indicates that the topological properties are not the decisive factor for monkeys' discrimination performance. In monkeys' discrimination, even when the hole is in a compatible ratio of 1:1.5, accuracy to the hole feature is still lower than shape difference. The effect of hole size in human subjects and its difference in the elicited event-related potentials will be reported in a separate paper. The difference between experimental paradigm (discrimination and the sameness–difference

Table 2
Comparison of averaged accuracy and RT to three groups' stimulus in three kinds of duration of presentation of the stimuli

	100 ms		50 ms		30 ms	
	AR (%)	RT (ms)	AR (%)	RT (ms)	AR (%)	RT (ms)
P–Ns	92.6 ± 5.6	545 ± 22	90.5 ± 6.6	523 ± 32	88.4 ± 3.1	535 ± 23
P–Nh	91.7 ± 7.6	526 ± 42	84.0 ± 7.2	523 ± 49	$49.4 \pm 6.6^*$	539 ± 37
P–Nsh	92.7 ± 3.0	524 ± 23	92.3 ± 3.4	546 ± 43	89.8 ± 3.3	543 ± 40

AR: accuracy.
$^*P < 0.05$ ANOVA in different duration of the presentation, $F(4, 44) = 21.3245$.

judgment (SDJ)) might be another reason for this discrepancy, since the different features in stimuli are a critical factor in the DT. So the role of the common features in stimuli becomes to be the aim of next experiment.

3. Experiment 2: concurrent matching to sample task

In a modified paradigm of the delayed matching to sample (DMS), monkeys learned concurrent associations of 2D objects with delayed reward (Gutnikov et al., 1997). This study demonstrates that neurons in temporal cortex show some certain object-specific activity during a display of objects, however, only a fraction of those neurons remain active after stimulus offset. In a delayed reward condition, the majority of object-specific neurons in the area cease firing before reward is given and can be detected. Another modified paradigm used the conventional DMS as a control task and found that activity of neurons in the inferior temporal cortex was related to a target picture in a pair-association task (Naya et al., 1996). Both of these two modified DSM paradigms kept the delayed reward, while the concurrent presentation of pictures for monkeys to sample is the basic difference. To inquire into the role of the common features in early visual processing, the DMS was modified to CMS, and the reward is released immediately after monkeys pointed at the matching picture in this experiment.

3.1. Materials and methods

After the previous experiment, monkeys used in current study were hold for at least one month before going to be trained for performing CMS. In this task, three figures were displayed simultaneously on the screen, with the sample figure at the top of the screen and the two matching figures, one of which is a distracter figure, on the lower left and lower right, respectively. The behavioral experiment comprised two sessions: learning and testing. In the first session, both of the two comparison figures were the same as the sample on the top of the screen and were displayed for 3000 ms. Monkeys were trained to touch either of comparison figures. After that one comparison figure was replaced by a figure with certain obviously different features and monkeys were trained to point the figure which was more similar to the sample. After monkeys' performance kept over accuracy of 90%, the display time was shortened to 1000 ms. Test session began as soon as monkeys' performance became stable again. The two comparison figures in the test session were the negative pairs in Table 1, and the display time was shortened to 100, 50, and 30 ms. Matching ratios of different figure pairs were compared using Binominal non-parametric test.

3.2. Results and discussion

In the training process of CMS, 5–7 days are needed to reach 90% accuracy for P–Ns figure pairs with the distinct change of Euclid geometric property, and P–Nsh figure pairs carrying both Euclid geometric and topological changes. At the same time, however, much more days (20–25 days) are needed for P–Nh figure pairs, which have topological distinction. Therefore, the learning curves here are similar to those in experiment 1.

Under different conditions, the sample figure was positive figure, and the topologically different figure Nh had been matched much more (above 75%) than the geometrically different figure Ns (below 20%) and Nsh (below 25%) with both differences when the presentation duration of the figures was shortened to 100 ms. The matching rate of Ns and Nsh was close to each other under the condition of 100 ms presentation (Table 3). The matching rate of all the figures Nh decreases about 10% when the presentation duration was shortened from 100 to 30 ms, although all of them are statistically higher than the matching rate of Ns and Nsh, which was shown in Tables 4 and 5.

The learning process and the matching rate are consistent with the result in DT that more mistakes have been made for topologically distinct figures. Human subjects in a similar experimental paradigm where the basic objects to be compared were wedge-like shape demonstrated that similarity comparison is highly sensitive to judgment context (Goldstone, Medin, & Halberstadt, 1997). The stimuli varied on three dimensions, which are angle, size, and hue, and four values on each dimension. Subjects' choice can be accommodated in terms of a dynamic property-weighting process based on the variability and a diagnosis of dimensions. Similar

Table 3
Matching ratios under 100 ms presentation

Group	Ns–Nh pair		Nh–Nsh pair		Ns–Nsh pair	
	Ns	Nh	Nh	Nsh	Ns	Nsh
1	0.112	0.888*	0.874**	0.126	0.508	0.492
2	0.098	0.902*	0.931**	0.069	0.494	0.506
3	0.105	0.895*	0.892**	0.108	0.503	0.497

* $P < 0.05$ vs. Ns.
** $P < 0.05$ vs. Nsh.

Table 4
Matching ratios under 50 ms presentation

Group	Ns–Nh pair		Nh–Nsh pair		Ns–Nsh pair	
	Ns	Nh	Nh	Nsh	Ns	Nsh
1	0.220	0.780*	0.806**	0.194	0.546	0.454
2	0.164	0.836*	0.892**	0.108	0.497	0.503
3	0.208	0.792*	0.901**	0.099	0.537	0.463

* $P < 0.05$ vs. Ns.
** $P < 0.05$ vs. Nsh.

Table 5
Matching ratios under 30 ms presentation

Group	Ns–Nh pair		Nh–Nsh pair		Ns–Nsh pair	
	Ns	Nh	Nh	Nsh	Ns	Nsh
1	0.291	0.709*	0.712**	0.288	0.569	0.431
2	0.308	0.692*	0.699**	0.301	0.509	0.491
3	0.279	0.721*	0.710**	0.290	0.546	0.454

* $P < 0.05$ vs. Ns.
** $P < 0.05$ vs. Nsh.

hypothesis can also be supported with our data with a less complicated stimulus set and clearer effect. According to the weighted ratio model of similarity (Lamberts, 1994), similarity matching depends on the ratio of the common features (Cfij) to the different features (Dfij). In experiments 1 and 2, the different and common features have been studied, respectively. So it is necessary to test both types of features simultaneously in a SDJ test.

4. Experiment 3: sameness–difference judgment

Different from the oral report used in the human subjects experiment (Chen, 1982), monkeys were trained to make the SDJ with go/no-go response. Go/no-go task was used for monkeys to discriminate between green (go) and red (no-go) light signals in a study (Tsujimoto et al., 1997), which reflected a mode of functional integration between visual perception and motor suppression.

4.1. Materials and methods

In this experiment three monkeys were trained to make a SDJ of two pictures displayed for 1000 ms at both sides of the screen. Monkeys' task was to touch the screen (go response) if those two figures were the same, and not to touch (no-go response) the screen if they were different. The training was step by step with the order of no-go response, go response and go/no-go response. The days needed for monkeys to reach the accuracy of 90% were compared among different figure pairs. After monkeys' performance kept stable, the presentation time was shortened to a certain value that the overall accuracy of every block reached about 50%. In the meanwhile, individual accuracy for different stimulus groups was compared to see which properties influenced the judgment task.

4.2. Results and discussion

It took about a week for monkeys to learn to make a difference judgment with a no-go response. And then about 2–3 days were spent for monkey to learn the sameness judgment with a go response. When the training went ahead to the session characterized by mixed SDJ task, an inconsistency of necessary training days appeared among different stimuli pairs. More learning time was needed with the increase of the figure similarity. It took monkeys 5–10 days to learn the task for the figures with distinct Euclid geometric feature (P–Ns), and 6–8 days for the figures with both Euclid geometric and topological distinct (P–Nsh). In contrast, 15–25 days were required for the figures carrying topological distinction (P–Nh). Therefore, the learning process to this task appeared to be similar to experiment 1.

Table 6
Accuracies of SDJ during 50 ms presentation for different group of figure pairs

Group	P–Ns (%)	P–Nh (%)	P–Nsh (%)
1	59	31*	61
2	56	36*	57
3	58	33*	60

* $P < 0.001$, P–Nh vs. P–Ns and P–Nsh, $F(2, 29) = 813.8$.

The overall accuracy was around 50% when the presentation duration was shortened to 50 ms. Under this condition, accuracy of the figure pairs with topological difference was significantly lower than other two kinds of pairs ($P < 0.001$, $F(2, 29) = 813.8$). There was no difference between accuracies of P–Ns pairs and P–Nsh pairs (Table 6).

Both of the learning process and the accuracy of the SDJ with the presentation duration of 50 ms demonstrated a striking resemblance to experiments 1 and 2, which indicates a consistent precedence of P–Ns and P–Nsh pairs over P–Nh pairs in visual processing. According to the explanation of go/no-go response (Tsujimoto et al., 1997), the stimuli pairs of P–Ns and P–Nsh produced much better function integration between perception and motor suppression than P–Nh pairs. The differences in accuracy reached the significant level when the presentation duration was shortened to 50 ms in go/no-go task, while it was 30 ms in the DT in experiment 1. This difference might be caused by the more complex process in go/no-go response than those in DT.

5. General discussion

Taken together the consistent results exhibited in these three different cognitive tasks demonstrate that it is much easier for monkeys to recognize figures with distinct Euclid geometric properties than figures with distinct topological properties. The visual discrimination process is subject to Euclid geometric properties of the figures. In contrast, distinct topological properties are more likely to be perceived as similar or the same features in similarity judgment and SDJ. Related to the study with human subjects (Chen, 1982), this result seems different. Since the possibility which attributes the discrepancy to experimental paradigm or condition has been excluded already, some certain species-specific effects could be accounted for explaining the discrepancy.

The study of Ponzo illusion with *macaca* monkey, chimpanzee and human subjects suggests that a lot of similarity appears in perception properties for these three species, however, it has been reported that certain significant difference exits between the human beings and non-human primates (Fujita, 1997). The reason for this inconsistency might be the distinct internal representation of 2D figures between species. However, this hypothesis is weakened by a finding, which suggests consistent similarity judgment of three-dimensional (3D) object with natural meaning between human beings and monkey (Sugihara, Edelman, & Tanaka, 1998). So the representation of 3D figures in monkey visual system is "similarly faithful to the parametric variation built into the stimulus set". It becomes to be reasonable here to test the different processing of naturally meaningful figures and simple geometric figures.

A uniform pathway of the visual representation is suggested with internal representation based on similarity (Edelman, 1998). Similar reference shapes are detected selectively. And visual world is thus represented with the proximal and distal similarity. So similarity judgment plays an important role in visual processing. According to Edelman, the proximal space is consisted of all kinds of "classifier", which are different prototypes. More similar stimuli are, nearer they will be in the internal space. The positive figure or the sample in the stimulus set of the current study might to be regarded as the prototype. The internal representation of the negative figures in the internal space depends on the comparison of their representation to the prototype. In the internal representation space of monkey, the distance between figures with Euclid geometric or both geometric and topological distinction must be larger than figures with topological distinction. While the distances in the internal representation space for human subject seems to be different from monkey because of certain species-specific difference.

A general topological analyzer (Hecht & Bader, 1998) in visual processing is proposed because the pattern discriminability is dependent on three topological features, including the number of disconnection, connection (holes), and inclusion relationships. Inconsistently, two of them lose their impact in visual discrimination for monkey. Also neural networks show that oscillator networks exhibit sensitivity to topological structure, which may develop a neurocomputational foundation for topological perception (Wang, 2000). Although topological structure of visual stimuli is perceived globally, there is another global feature in our stimuli set, shape. Global processing precedence has been reported for many cases. Perceptual advantage of globally conveyed information (Proverbio, Minniti, & Zani, 1998) is stronger than processing of topological features.

Since we used simple geometric figure as stimulus, the global precedence is embodied in the geometric features in this experiment, while topological property is not popped out. Similarly, a global shape detecting mechanism is used for judgments of circularity while local topological feature is overlooked (Hess, Wang, & Dakin, 1999). However, in monkey perception the predominant role of hole which is embedded in face component reveals the context-dependent effect between Euclidean and topological geometric features in pattern recognition of 2D figures (Shen, Zhang, & Chen, 2002). Therefore, there should not be absolutely invariant precedence in perception. Instead, it depends on subject species, stimulus set, and ecological significance of the perceiving process.

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